LLNL Environmental Restoration Division (ERD)
Standard Operating Procedure (SOP)

ERD SOP 3.3: Hydraulic Testing (Slug/Bail)—Revision: 3

AUTHOR(S):
Z. Demir and B. Clark

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APPROVALS: **Date**

Albert L Lamarre 3/21/03
Division Leader

3/20/03
Environmental Chemistry and Biology Group Leader

CONCURRENCE: **Date**

Rebecca Goodrich 3/20/03
QA Implementation Coordinator

1.0 PURPOSE

The purpose of this SOP is to determine saturated hydraulic conductivity of the sediments near the well screen under *in situ* conditions without pumping the well.

2.0 APPLICABILITY

This procedure is applicable for slug/bail hydraulic testing. Slug/bail tests are only recommended for wells that produce less than 1 gallon per minute.

3.0 REFERENCES

3.1 Bower, H. (1978), *Groundwater Hydrology*, McGraw-Hill, New York, N.Y.

3.2 Bower, H. and R. C. Rice (1980), "A Slug Test for Determining the Hydraulic Properties of Tight Formations," *Water Resources Research* **16** (1), pp. 233–238.

3.3 Cooper, Jr., H. H., J. D. Bredehoeft, and S. S. Papadopoulos (1967), "Response of a Finite-Diameter Well to an Instantaneous Charge of Water," *Water Resources Research* **13** (1).

3.4 DOI (n.d.), *Ground Water Manual*, U.S. Department of the Interior Publication.

3.5 Earlougher, R. C. (1977), *Advances in Well Test Analysis*, Society of Petroleum Engineers of AIME.

3.6 Ferris, J. G. and D. B. Knowles (1954), "The Slug Test for Estimating Transmissivity," *U.S. Geological Survey Groundwater Note 26*.

3.7 Freeze, R. A. and J. A. Cherry (1979), *Groundwater*, Prentice-Hall, Inc., Englewood Cliffs, New Jersey.

3.8 Hvorslev, M. J. (1951), *Time Lag and Soil Permeability in Ground-Water Observations*, U.S. Army Corps of Engineers, Bull. 36.

3.9 Johnson Division, UOP, Inc. (1966), *Groundwater and Wells.*

3.10 Lohman, S. W. (1972), "Ground-Water Hydraulics," *U.S. Geological Survey Paper 708*.

3.11 Neuman, S. P. (1972), "Theory of Flow in Unconfined Aquifers Considering Delayed Response of the Water Table," *Water Resources Research* **8** (4), p. 1031.

3.12 Papadopoulos, S. S., J. D. Bredehoeft, and H. H. Cooper, Jr. (1973), "On the Analysis of Slug Test Data," *Water Resources Research* **8** (4).

3.13 Todd, D. K. (1980), *Groundwater Hydrology*, 2d ed., John Wiley & Sons, New York, N.Y.

3.14 U.S. Department of the Interior (n.d.), *Ground Water Manual*, Washington, D.C.

3.15 Walton, W. C. (1970), *Groundwater Resource Evaluation*, McGraw-Hill, New York, N.Y.

4.0 DEFINITIONS

See SOP Glossary**.**

5.0 RESPONSIBILITIES

5.1 Division Leader

The Division Leader's responsibility is to ensure that all activities performed by ERD at the Livermore Site and Site 300 are performed safely and comply with all pertinent regulations and procedures, and provide the necessary equipment and resources to accomplish the tasks described in this procedure.

5.2 Hydrogeology Group Leader (HGL)

The HGL is responsible for ensuring that proper procedures are implemented for field activities (i.e., drilling, borehole logging and sampling, monitor well installations and development) and to oversee the disposal of investigation derived wastes.

5.3 Subproject Leader (SL)

The SL is responsible for the overall investigation, planning, and assessment and remediation within a study or treatment facility area.

5.4 Hydrogeologist (HG)

The HG is responsible for preparing the Hydraulic Test Plan (Attachment B) and assisting the field personnel in conducting his/her responsibilities.

5.5 Field Personnel

Field personnel are responsible for conducting and documenting hydraulic testing according to this procedure.

6.0 PROCEDURES

6.1 Discussion

6.1.1 During the slug test, a slug of known volume is lowered into the well displacing that same volume of water. Over time, typically a few hours, the water level returns to static. During the test, water-level measurements are recorded using a pressure transducer and a data logger. These measurements, plotted against time, produce a curve which is then compared to type-curves to determine values of T and K. For a bail test, the slug is removed from the well, and water-level measurements are collected similar to the slug test.

6.1.2 The advantages and limitations of using slug/bail tests to estimate hydraulic properties include: 1) estimates can be made *in situ*, and errors incurred in laboratory testing of disturbed samples are avoided; 2) tests can be quickly performed at a relatively low cost, because a pumping well and observation wells are not required; 3) the hydraulic conductivity of small volumes within an aquifer can be estimated; 4) no treatment, collection, or disposal of pumped water is necessary; 5) only the hydraulic properties of the material very near the well are estimated, and they may not be representative of the average hydraulic properties of the area; 6) certain assumptions are made in the analysis, and if they are inconsistent with the geologic conditions at the site, the slug/bail test results may be invalid; 7) the storage coefficient *(S)* usually cannot be determined; and 8) sufficient data for analysis may not be collected if the hydraulic conductivity of the screened material is relatively high.

6.2 Office Preparation

6.2.1 Review the Hydraulic Testing Plan (Attachment B) with the SL.

6.2.2 Review the Daily Operations Guide, associated SOPs, and appropriate sections of the Site Safety Plan. Information on depth to water, depth of well, screened interval, casing size, and pump size and type is obtained from the Data Management Team (DMT) for established wells, or from the drilling coordinator for new wells.

6.2.3 Coordinate schedules/actions with SL or project HG, as appropriate.

6.2.4 Review the operator's manual provided with the electronic data logger, if appropriate.

6.2.5 Check out and ensure the proper operation of all field equipment. Ensure that the electronic data logger is fully charged, if appropriate. Test the electronic data logger and pressure transducers using a container of water (e.g., sink or bucket of water). Always bring additional transducers in case of malfunctions.

6.2.6 Obtain the Hydraulic Test Logbook and a sufficient number of field forms to complete the field assignment.

6.3 Field Preparation

6.3.1 If the well has a Well Wizard bladder pump or a similar instrument installed, it must be removed at least one day before the test is conducted to allow the water level to return to static.

6.3.2 Locate monitor wells to be tested and appropriate decontamination areas.

6.3.3 Assemble appropriate testing equipment listed in the Equipment Checklist (Attachment A).

6.3.4 To avoid cross-contamination, bailers or measuring devices should be cleaned before and after each test. If water is added to the monitoring well, it should be from an uncontaminated source and be transported in a clean container. Decontaminate the transducer and cable as specified in SOP 4.5, "General Equipment Decontamination."

6.3.5 Calibrate all gauges and transducers before conducting slug test according to SOP 3.2, "Pressure Transducer Calibration." Document instrument calibration in the Hydraulic Test Logbook.

6.3.6 Measure initial water level in monitor well or piezometer according to SOP 3.1, "Water Level Measurement," and record on Hydraulic Test Field Sheet (Attachment C).

6.3.7 Before beginning the slug test, enter and record information in the electronic data logger. The type of information will vary depending on the model used. When using different models, consult the operator's manual for the proper data entry sequence to be used. For example, the following data is entered into the Enviro-Labs Model DL-120-MCP Data Logger:

1. Baud rate.
2. Station ID.
3. Date (YY/MM/DD).
4. Time (HH:MM:SS).
5. Scale factors for each channel.
6. Logging sequence.

6.3.8 Test wells from least contaminated to most contaminated, if possible.

6.4 Operation

The following general procedures will be used to collect and report slug/bail test data. The procedures required for a particular slug/bail test may vary slightly from those described, depending on site conditions. Modifications to the test procedures should be documented on the Hydraulic Test Field Sheet (Attachment C) and Slug Test Schematic (Attachment D).

6.4.1 When the slug/bail test is performed using an electronic data logger and pressure transducer, most of the data will be electronically stored internally or on computer diskettes or tape. The information will be transferred directly to the main computer and analyzed. A Hydraulic Test Field Sheet (Attachment B) with supplemental information and a computer printout of the data should be maintained with the DMT as documentation.

6.4.2 The time required to complete a slug test is a function of the volume of the slug, the transmissivity of the formation, and the well casing size. The slug volume should be large enough that a sufficient number of water level measurements can be made before the water level returns to equilibrium conditions. Test length may range from less than a minute to several hours.

6.4.3 Slug tests must be conducted on relatively undisturbed wells. If a test is conducted on a well that has recently been pumped, measure the water level within 0.1 ft of the static water level before sampling. At least one week should elapse between well development and the slug test.

6.4.4 The slug will have to remain completely submerged throughout the test, so the height of the static water column must be greater than the length of the slug.

6.4.5 A pressure transducer must hang below the bottom of the submerged slug so a portion of the water column must be available for the transducer.

6.4.6 The slug diameter must be small enough so that it will not disturb the transducer cable when the slug is lowered.

6.4.7 Although a larger slug is desired when possible, using a large slug that is unwieldy can result in unnecessary difficulties and/or damage to the pressure transducer.

6.4.8 Well diameter, screened interval, total depth, and most recent, depth-to-water information should be used to determine the appropriate slug size. A slug of appropriate size may need to be constructed.

Note: In general, slug size will not be restricted by the height of the water column, but double check to prevent having to redo a test.

6.4.9 The Hydraulic Test Field Sheet (Attachment B) is used to record observations and supplemental information. Complete the form as follows:

1. Site Location. Brief description of the general location of the well.
2. Well ID. Unique number assigned to each well where measurements are taken.
3. Date. The date of the test.
4. Make of logger used (Campbell or Hermit) and the make and serial number of the transducer used.

5. Slug Dimensions or Volume of Water. Dimensions of the slug or displacement object in tenths of feet.
6. Personnel. Initials of personnel performing field measurements or collecting samples.
7. Test Type. The slug device is either injected (slug) or withdrawn (bail) from the monitor well. Note the appropriate test type.
8. Comments. Appropriate observations or information for which no other blanks are provided.
9. Elapsed Time (min:sec). Cumulative time readings from beginning of test to end of test in minutes and seconds.
10. Depth to Water (ft). Depth of water recorded in tenths and hundredths of feet.

6.5 Procedure for Conducting a Slug/Bail Test.

6.5.1 Measure the static water level in the well, and record in the Hydraulic Test Logbook and on the Hydraulic Test Field Sheet (Attachment C). The point and time of measurement should be noted on the Hydraulic Test Field Sheet (Attachment C) and in the wellhead logbook.

6.5.2 Cover sharp edges of the well casing with duct tape to protect the transducer cables.

6.5.3 Connect the transducer cable to the electronic data logger.

6.5.4 Slowly lower the transducer and cable down the well to a depth below the slug submergence for the test, but at least 1 ft from the bottom of the well. Be sure this depth is within the design range stamped on the transducer. To keep the transducer at a constant depth, securely tape the transducer cable to a stationary object.

6.5.5 Firmly tie one end of the rope to the slug. From the top of the slug, measure a length slightly greater than the depth-to-water, and mark the rope with a duct tape tag. Then, measure the length needed at the duct tape tag to hang the slug a few inches above the static water level, and mark this with a second duct tape tag. Account for any possible stretching of the rope.

6.5.6 Tie the other end of the rope to an anchor so that the slug can be lowered within a few inches of the water level.

Note: Account for “stretch” of the rope by being a little conservative in estimating where the slug will hang.

6.5.7 Slowly lower the slug into the well and let it hang a few inches above the water as mentioned in Step 6. Have the data logger display the transducer readout while lowering the transducer. If the slug does contact the water, an immediate change will be seen. On the logger readout, use the lower duct tape tag as a reference point.

Note: Touching the water with the slug is not always disastrous. If the slug does touch the water, pull it back up a few inches and see if the water level returns to static in the next few minutes or so.

6.5.8 Once the slug is hung, set the data logger to log according to the hydraulic Test Plan (Attachment B).

6.5.9 To begin the test, turn the logger on 5 seconds prior to lowering the slug. It is preferable to begin logging on an even minute and to lower the slug 5 seconds after (e.g., 10:00:00 "logging on," 10:00:05 "slug lowered"). Quickly lower the slug to the second duct tape mark (see Step 5) and tie off the rope. Do not splash the water.

Note: Sometimes, it is possible to tie the rope to two different anchors so that when the rope is untied from the first position (slug just above the water), it can be dropped and the second anchor will hold it at the desired depth (see Attachment D "Before Start of Slug Test" and "After Start of Slug Test").

6.5.10 Another method is to introduce a solid cylinder of known volume to displace and raise the water level, allow the water level to restabilize, and remove the cylinder. It is important to remove or add the volumes as quickly as possible because the analysis assumes that an instantaneous change in pressure is created in the well. It is important to ensure that the slug is completely submerged if introduced.

6.5.11 Note on the logger readout, the initial rise in the water level and see if it corresponds with the calculated rise. Since the water level changes fairly rapidly at first, it may be necessary to scroll back through the logged data to determine the first (highest) point.

Note: This initial rise calculation often does not exactly correspond with the logged initial rise, but it should be relatively close.

6.5.12 At some point during the test, take at least one depth-to-water measurement with the water level probe to ensure the transducer is reading correctly.

6.5.13 When the water level has returned to static level, the bail test is then performed.

6.5.14 Reset logging mode on an even minute, then pull out the slug as quickly as possible. Note the decrease in water level.

6.5.15 At each reading, measure depth to water (to the nearest 0.01 ft) and record time when pressure change is at time zero. The number of depth-time measurements necessary to complete the test are variable. Frequent measurements should be made so that the change in water level between two consecutive measurements is <5% of the initial change. It is critical to make as many measurements as possible in the early part of the test.

6.5.16 Continue measuring and recording depth-time measurements until the water level returns to within 10% of equilibrium conditions.

6.5.17 The test is complete when the water level has returned to static level, and the log equipment can be broken down.

6.6 Post Field Operation

6.6.1 Decontaminate or dispose of equipment and rope according to SOP 4.5.

6.6.2 If using an electronic data logger:

1. Stop logging sequence.

2. Save memory.
3. Disconnect battery at the end of the testing activities.

6.6.3 Replace testing equipment in storage containers.

6.7 Office Post Operation

6.7.1 Inventory sampling equipment and supplies. Repair or replace all broken or damaged equipment.

6.7.2 Replace expendable items.

6.7.3 Return equipment to storage area and report incidents of malfunctions or damage.

6.7.4 Review Hydraulic Test Logbook and field forms for completeness.

6.7.5 Deliver original forms, logger data, and logbooks to the project HG. Deliver copies of documentation to the DMT, HGL, or SL, as appropriate.

6.7.6 Interpret slug/bail test field results with project HG, HGL, or SL. Analyze slug/bail test using appropriate software packages or graphical solutions.

6.7.7 Send data logger or pressure transducers to factory for recalibration, if needed.

7.0 QA RECORDS

7.1 Logbooks

7.2 Hydraulic Test Field Sheet

8.0 ATTACHMENTS

Attachment A—Equipment Checklist

Attachment B—Hydraulic Test Plan

Attachment C—Hydraulic Test Field Sheet

Attachment D—Slug Test Schematic

Attachment A

Equipment Checklist

Equipment Checklist

____ 12-volt battery

____ Appropriate references and calculator

____ Aquifer test sheets

____ Calculator, clip board

____ Duct tape

____ Electric water-level indicator

____ Electronic data logger (if transducer method is used)

____ Interface probe

____ Rope (should very little “stretch”)

____ Semilog graph paper (if required)

____ Slug (steam cleaned prior to use)

____ Steel tape (subdivided into tenths of feet)

____ Stopwatch or watch with second hand

____ Tape measure (subdivided into tenths and hundredths of feet) or other water-level measuring device

____ Watch with a second hand

____ Water-pressure transducer (if test is anticipated to last overnight, a barometric pressure transducer should also be used)

____ Waterproof ink pen and logbook

Attachment B

Hydraulic Test Plan

HYDRAULIC TEST PLAN

GENERAL INFORMATION		By:
Location:	Livermore Site ❑ Site 300 ❑ Area:	
Test Type: (1-hour drawdown, longterm, step flow or drawdown, slug, facility startup)		
Test Well Name(s):		
Expected Start Date:		
Duration of Test:		
Treatment Unit or Method:		
Comments:		

TEST OBJECTIVE(S)	By:

TEST DESCRIPTION AND SPECIAL INSTRUCTIONS	By:

GROUND WATER CHEMISTRY IN TEST WELL(S)	By:

EXTRACTION WELL(S) DESCRIPTION			By:
Well(s)			
Screen Interval (ft-bgs/bmp)			
Pump Intake (ft-bgs/bmp)			
Depth to static water level (ft-bmp)			
Available Drawdown (ft)			
Extraction Flowrate (gpm)			
(only for step flowrate tests) Steps <Flowrate (gpm) - Duration(hrs)> 1 2 3 4 5			
Estimated Volume to be Extracted (gal)			
Pump Type and Size			
Extraction Flowrate Measurement			
Comments:			

Notes: **bgs**- below ground surface elevation, **bmp**- below measurement point elevation

SAMPLING PROTOCOL		By:
Sample Date/Time – **I**nfluent/**E**ffluent	Sample form Well(s)	Analysis (i.e. E601)
Initial >		
Final >		
Comments:		

WATER LEVEL MEASUREMENT SPECIFICATIONS	By:
Extraction Well:	
Observation Wells:	Shown on attached figure: Yes ❑ No ❑
Wells instrumented with transducers:	
Wells to be hand-measured:	
Collection of water levels in instrumented wells using data loggers and hand measured wells:	
Log Barometric Pressure Readings	Yes ❑ No ❑
PRIOR TO PUMPING: Log background water levels every 15 minutes for at least 24 hours prior to test.	
DURING PUMPING: Log water levels during test as indicated below: TEST WELL: Logarithmically increasing frequency ❑ or Linear at 15 minute intervals ❑ OBSERVATION WELLS: Logarithmically increasing frequency ❑ or Linear at 15 minute intervals ❑ HAND MEASURED WELLS: Linear at 60 minute intervals ❑	
DURING RECOVERY: Log water levels after pump shut-in as indicated below for at least 24 hours: TEST WELL: Logarithmically increasing frequency ❑ or Linear at 15 minute intervals ❑ OBSERVATION WELLS: Logarithmically increasing frequency ❑ or Linear at 15 minute intervals ❑ HAND MEASURED WELLS: Linear at 60 minute intervals ❑	
NEARBY EXTRACTION WELLS: Inform technicians of nearby extraction wells/facility to maintain constant flow rates in all extraction wells during the test. Inform them of potential water level changes in wells due to hydraulic testing.	
Comments:	

Note:
Verify availability of data loggers, transducers, and cable with Field Coordinator (Billy Clark).
Logging frequencies are subject to change as directed by LLNL Hydrogeologist or Field Coordinator.

GROUND WATER DISCHARGE	By:
Estimated Volume of ground water to be discharged (gals):	
Type of water storage tank and capacity: *(NOTE: see estimated volume to be extracted above to determine if adequate storage is available)*	
Discharge Location:	
Type of Discharge Permit Required ❑ NPDES: ❑ City of Livermore: ❑ None / Other (explain):	
Treatment of ground water required to comply with Discharge Permit:	Yes ❑ No ❑
Type of treatment, if necessary:	
Estimated Chemistry of ground water to be discharged:	
Comments:	

Attachment C

Hydraulic Test Field Sheet

HYDRAULIC TEST FIELD SHEET

Site	❑ Livermore Site ❑ Site 300	Page ___ of ___	By:
Test Well		Treatment Unit	
Test Type		Data Logger(s)	
Comments			
Totalizer: Start: (gals)	End:	> Total Gallons Extracted:	

Data Logging Start Date: / / Memory Loc.: Data Logging End Date: / / Memory Loc.:					Hydraulic Test Start Date: / / Hydraulic Test End Date: / /				
channel									
well ID									
xducer (psi)									
date/time									

Attachment D

Slug Test Schematic

WEISS ASSOCIATES

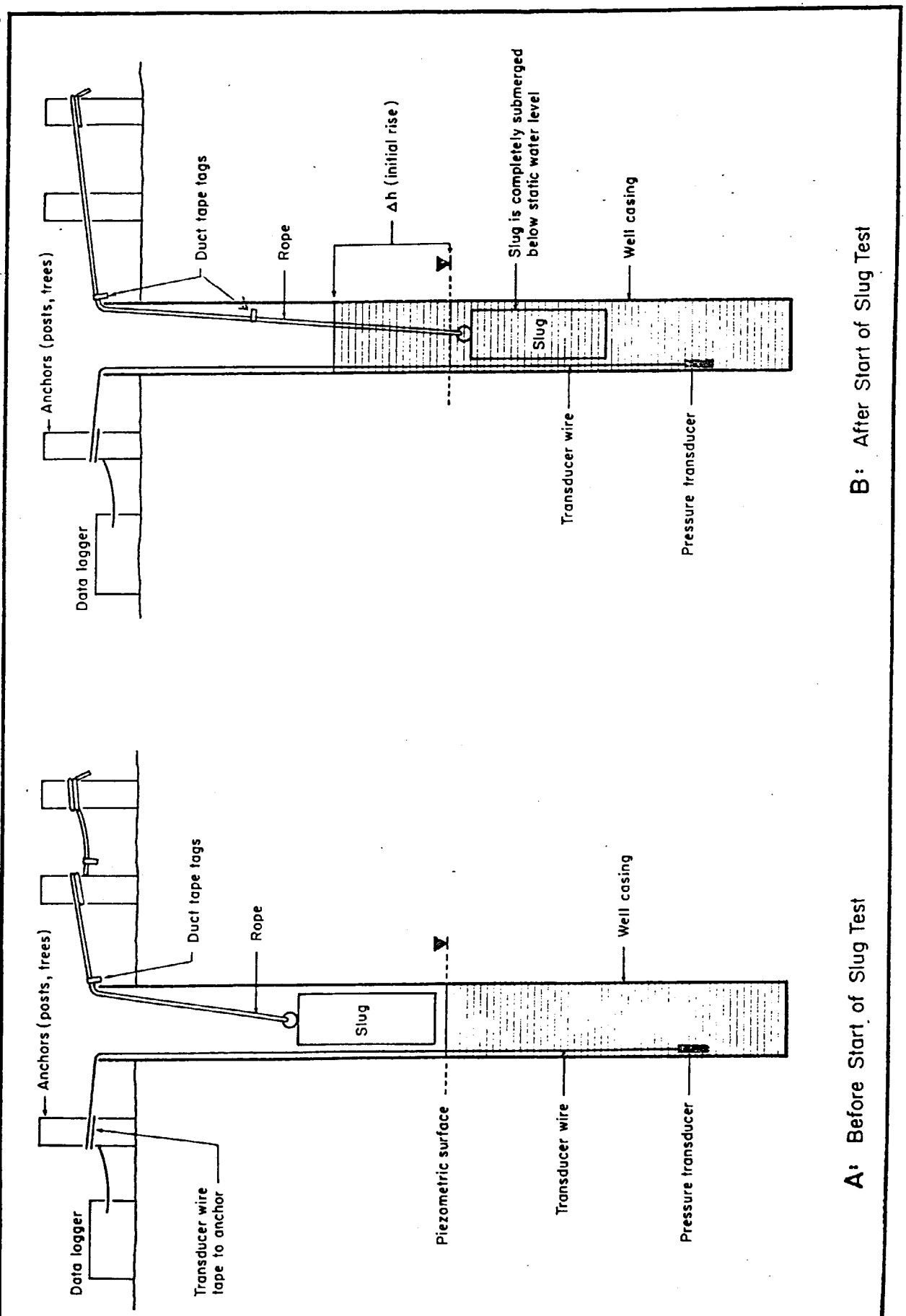

Figure 5-1 Slug Test